MANEUVER DESIGN FOR GALILEO JUPITER APPROACH AND ORBITAL OPERATIONS

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ABSTRACT

Following the successful release of the Galileo Probe in July of 1995, navigation efforts focused on implementing the critical Io approach and Jupiter orbit insertion strategy that had been refined over the previous decade, Actual events on approach would significantly alter these plans. The most significant event affecting the navigation plan was an onboard tape recorder anomaly, which, as will be shown, would have a profound effect on the plans and assumptions of the navigation strategy for approach and orbit insertion. This paper addresses the analysis, constraints, contingency planning and design evolution of trajectory correction maneuvers enabling the completion of these events, which lead to the first ever atmospheric entry Probe and Orbiter of an outer planet. An'analysis of the original navigation plan is presented to verify the viability of that strategy under nominal circumstances. A presentation of orbital phase performance and future mission operations plans is also included.

1. INTRODUCTION

As this paper is being written, the Galileo spacecraft has been in orbit about Jupiter for approximately 16 months and continues to provide a steady stream of intriguing, exciting and unique science data (Refs. [1] and [2]) from the thirteen scientific investigations (Ref. [3]). The probe mission exploring the atmosphere of Jupiter was a great success and has produced a bounty of scientific information that will be the subject of analysis and discussion for years to come (Ref. [4]). From an engineering point of view, the most difficult and risky phases of the mission are behind us. The current focus of engineering efforts of the flight team continues to be the maintenance of a healthy platform for the suite of scientific instruments, and the navigation of the orbital tour in a manner that maximizes the quality of the data return and the probability for extending the mission an additional two years.

This paper discusses the nominal navigation strategy for Jupiter operations as introduced in Refs. [5] and [6] and how these plans were adjusted as a result of inflight events. The initial focus is upon those events surrounding Jupiter approach and orbit insertion, which occurred in late 1995, while the remaining sections of the paper discuss some performance results from the orbital tour. Refs. [7] and [8] discuss navigation results and strategy beginning with the launch of the Galileo spacecraft in October of 1989.

2. NOMINAL JUPITER APPROACH AND INITIAL ORBIT NAVIGATION STRATEGY

A high level overview of the maneuver strategy for the Io Approach and Orbit Insertion phase of the mission is illus trated below.

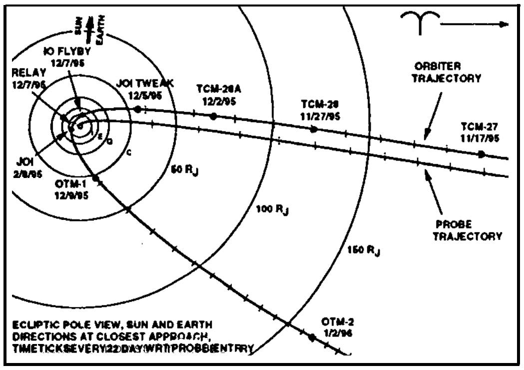

Figure 1. Jupiter Approach and Insertion Maneuvers

The approach sequence of events included five Io approach trajectory correction maneuvers, or TCMS (of which three are shown in the above figure), a tweak (or update) of the onboard Jupiter Orbit Insertion maneuver (JOI) burn parameters at JOI -2 days, a close flyby of Io, Probe Relay, JOI, two post-JOI clean-up maneuvers on either side of solar conjunction, and the Perijove Raise Maneuver (PJR) located near apojove of the insertion orbit (not shown). A complete list of maneuver locations and velocity changes (AV) is summarized later in the paper in Table 2.

The close Io flyby was critical to the orbit insertion success since it provided a significant gravity assist, reducing the JOI AV requirement by approximately 175 m/see to 644 m/see. As a result of this Io gravity assist, any altitude deviation from the planned Io flyby altitude of 1000 km would directly result in a change to the AV necessary at JOI. An uncorrected Io flyby altitude error of 10 km is approximately equivalent to a 0.1 % JOI execution error, as measured against the propellant cost to correct the trajectory back to the nominal. The goal of the pre-Io TCMS was to minimize the de] i very error with respect to the Io target. Delivery error predictions were such that a significant Io flyby altitude error was likely even after the successful implementation of TCM-28A (the last Io approach maneuver). Ref. [5] predicted an altitude uncertainty of 54 km (1σ) at the time of TCM-28A.

An opportunity was provided to detect and compensate for most of the flyby error by providing for a late change to the required JOI burn AV magnitude, the nominal value already (at that time) stored onboard the spacecraft. In the nominal sequence of planned events, a tweak of the nominal JOI burn parameters (AV, backup burn durations) was planned to be uplinked to the spacecraft 3 days after the execution of TCM-28A (Ref. [5] predicted the altitude σ to decrease to 26 km). The JOI tweak was a powerful tool for minimizing the effect of Io flyby altitude errors on mission AV costs. Given the best estimates projected for the Io delivery errors on approach to Jupiter, there was a high probability of being in a situation where a tweak would have been desirable, from a propellant minimization viewpoint.

There was a large increase in AV cost for delaying the correction of Io altitude errors from the JOI tweak opportunity to OTM- 1. If the JOI tweak was not exercised in the general case, the OTM- 1 bias could easily have become large. Since the AV capability at OTM- I was limited by constraints on both execution duration (17 hour limit) and onboard memory, a AV bias introduced by an Io flyby error could be large enough such that OTM-1 would not be able to fully correct the combination of the flyby error and the JOI execution error. There was a factor of three increase in AV cost for delaying the correction of Io altitude errors from the JOI tweak opportunity to OTM- 1, and an additional factor of three cost for delaying any OTM- 1 corrections to the OTM-2 opportunity (approximation depends on the actual direction of the error).

Real-time decisions were to determine which of the activities discussed above could be safely deleted. These decisions were to be based upon frequent orbit determination updates during the approach and insertion phases. The strategy was robust to single event failures (such as the loss of a single maneuver or tweak) and provided the trajectory control opportunities necessary to ensure a successful orbit insertion and orbital tour.

Any residual flyby error (that could not be accounted for by the JOI tweak) and execution errors of the JOI maneuver itself, were planned to be corrected by the sequence of maneuvers beginning at the first orbit trim maneuver (OTM-1), 1.5 days after JOI execution. The two main clean-up maneuvers, OTM- 1 and OTM-2, were separated by nearly four weeks as these two maneuvers spanned the solar conjunction period. During this period the spacecraft would remain in a quiescent state, awaiting the telecommunications link to improve sufficiently to where the spacecraft could be reliably commanded,

PJR was the first of the sequence of maneuvers targeting to the final aimpoint at the Ganymede I (G 1) encounter. The date of PJR was allowed to move (to minimize propellant usage) to any of 11 dates over the interval from March 13, 1996 to March 23, 1996 (nominal date was March 18, 1996), the actual date being selected after OTM-1 had executed.

The ground system and spacecraft operations strategy during the approach and insertion phases of the mission was quite complex. It was clearly desirable to minimize the number of engineering activities required on the ground and by the spacecraft during this crucial phase of the mission. This desire, however, would be balanced against propellant cost issues associated with delaying corrections until after orbit insertion.

3. SPACECRAFT PROPULSION SYSTEM OVERVIEW

All propulsive velocity changes required in the Galileo mission are implemented by the retropropulsion module (RPM) housed within the spun section of the spacecraft. The propulsion system (discussed extensively in Ref. [9]) was provided by the Federal Republic of Germany and built under contract by Daimler-Benz Aerospace (DASA). It is a bipropellant, helium-pressure-fed system with monomethyl hydrazine as the fuel and nitrogen tetroxide as the oxidizer (following the PJR maneuver in March of 1996, pyres were fired to isolate the propellant tanks from the helium pressurant).

The RPM includes twelve 10 Newton thrusters and one large 400 Newton main engine (operated in pulsed mode and continuous mode respectively). The ION thrusters are separated into two clusters of six thrusters each, and are used for trajectory correction maneuvers and for spacecraft turns and spin rate control. Four of the 10N thrusters (used for PULZ maneuvers) and the 400N engine are oriented parallel to the spacecraft spin axis. These thrusters impart velocity changes, or AV, in the spacecraft's -Z direction. Two thrusters are canted 10° from the lateral direction and implement AV anywhere within the plane perpendicular to the spin axis, through proper timing of the thruster firings as the spacecraft rotates (used for LAT maneuvers). There are no thrusters positioned to effectively implement a AV in the spacecraft's +Z direction. Two P-thrusters, typically used together for precession maneuvers. are canted 21" about the lateral plane (cant angle designed to limit thruster plume impingement on the high gain antenna). When one of these thrusters (specifically the P 1A thruster) is pulsed every 180° of rotation,. a AV in the +Z direction is implemented (used for POSZ maneuvers). Due to the 21° cant angle of this thruster, AV in the +Z direction is approximately 3 times more costly, in terms of propellant, than the same AV in the -Z direction. The 400N engine has been used three times in the mission (the nominal plan), providing large velocity changes at the Orbiter Deflection Maneuver (or ODM, two weeks after probe release), JOI, and PJR. There is no plan to use this engine again (Table 2 summarizes the implemented maneuver ΔVs).

The spinning ION thruster configuration allows for a wide variety of methods for implementing a particular AV vector. For "vector mode" maneuvers the spacecraft does not change orientation during the activity. An arbitrary AV vector is implemented through the sequential firing of the axial (-Z thrusters or P l A thruster) and lateral thrusters. The nearly orthogonal AV components form the desired AV vector. This mode can be expensive in terms of propellant due to the sum of the components (rather than the resultant AV) being implemented, as well as the high cost if the axial component happens to be in the +Z direction. Implementation constraints, the operational advantages of not turning the spacecraft, and propellant cost usually determine when the vector mode strategy will be used. Typically, in the absence of constraints, the optimum mode for maneuver implementation involves a reorientation of the spacecraft attitude, followed by a burn to complete the required velocity change. Reorientation of the spin axis is accomplished through gyroscopic action induced by thruster supplied torque.

4. CONSTRAINTS AND CONTINGENCY CONSIDERATIONS

The overall orbit insertion strategy involved many maneuver design trade issues. There are a variety of constraints and contingency considerations that can enter into the maneuver design process that affect the maneuver strategy. Some of these will be touched upon here, others are discussed in Ref. [8]. Each of the maneuvers shown in Figure 1 was planned to be implemented in vector mode (except for OTM-2) at the same inertial attitude. Any change in attitude during the critical phase and solar conjunction period, together spanning from approximately 20 days before Io until 26 days after Io, would have introduced a host of non-nominal attitude fault scenarios, complicating an already difficult planning task. This constraint only introduced difficulties in the planning for OTM- 1 as the small approach maneuvers would not benefit greatly from turning and JOI had always been constrained in the mission design to be an axial maneuver, nearly aligned along the spacecraft to Earth direction.

The JOI 400N burn was to require approximately 49 minutes burn time to achieve the AV of 644.4 m/sec necessary to get into the proper orbit about Jupiter to link with the desired orbital tour trajectory. In a nominal scenario, burn termination would be tightly controlled by non-redundant accelerometers. Figure 2 summarizes some of the accuracy parameters of the 400N engine and accelerometers for the JOI burn, as well as some key execution error milestones for the nominal navigation strategy.

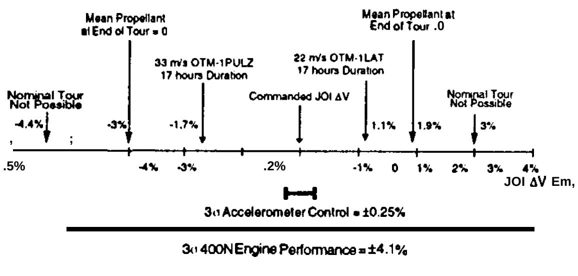

*Figure 2. Impact of **JOI** Execution Errors For Maintaining the Nominal Tour.*

Contingency strategies and fault protection parameter selections would provide the necessary backup to the accelerometers. In the presence of many onboard detected faults, the orbit insertion sequence was robust enough to ensure that the insertion burn would proceed for a minimum burn time (MIN), and no longer than a maximum burn time (MAX). Selection of these backup burn control parameters was critical. The accelerometers would only be active in the burn termination logic over the range of MIN to MAX burn time. The MIN/MAX time selections had to consider orbit capture, allow adequate opportunity for the accelerometers to terminate an under/over performing engine, yet limit the JOI burn duration such that if a fault occurred, forcing burn termination to occur at either the MIN or MAX time, there would be sufficient propellant to correct the AV error. A third backup timed option would use another selectable burn cutoff time referred to here as NOM, for nominal burn duration.

Different faults could cause the backup logic to use either the MIN. NOM or MAX backup timed cutoff options, As an example, a detectable onboard fault (such as an attitude control system power interruption, POR) during the burn would cause the logic to disregard the accelerometer information and terminate the burn at NOM time, regardless of the actual sensed engine performance (i.e. JOI would revert to a timed burn, subject to execution errors defined by the engine performance uncertainties given in Fig. 2). The capability to revert to a NOM burn time was added during the interplanetary phase of the mission after it became apparent that the propellant costs were too great at OTM- 1 to allow all faults to use either the MIN or MAX backup option exclusively. This same fault occurring during the burn, but after MIN time, would result in the issuance of commands to terminate the burn as soon as possible (in this instance the burn would stop approximately 20 seconds after the fault), possibly well before NOM time. Engine performance uncertainties going into this burn were too large (see Fig. 2) to allow for a simple timed burn to be the nominal JOI termination strategy. The potential propellant costs for this strategy were excessive and could not be tolerated in the nominal plan without planning for a redesign of the orbital tour and the subsequent sequences as part of the strategy (clearly undesirable in a no-fault scenario).

The final selected parameters for contingency JOI burn durations were consistent with JOI AV errors of -4% for MIN, -0.5% for NOM and +6% for MAX (assuming nominal engine performance). Potentially large propellant costs associated with the selection of this wide of a range of backup time parameters was balanced against the likelihood of the faults which could lead to those costly scenarios. A functional accelerometer producing bad data is the most credible scenario causing the burn to terminate at MAX time (by itself, the engine performance uncertainty would indicate a very small probability of this event). Excluding this unlikely fault scenario leads to increasing the time span from MIN to MAX, allowing an opportunity for the accelerometers to terminate the burn over a wider range of engine performance values (a significant benefit in a no-fault scenario as the JOI calibration data came from only one in-flight performance data point, namely ODM). However, recall that any fault during the JOI burn after MIN time would initiate burn termination. Advancing the MIN time to a point too early in the burn would increase the vulnerability to credible faults (such as a radiation induced POR), resulting in a severe underburn. This is the reason for the narrower range on the MIN side of the burn.

The biased selection for NOM results from the OTM-1 vector mode constraint, The optimum bias for JOI for a timed burn, a duration defined by NOM, is -0.5% (as determined by the mean expected cost for a timed cutoff). JOI overburn trajectory corrections require more propellant than equivalent JOI underburn trajectory corrections. In addition to JOI consuming more propellant in an overburn scenario, the propellant cost is compounded when the OTM-1 POSZ inefficiency is considered. As a result, a characteristic of JOI overburns is the requirement for more costly LAT maneuvers at OTM- 1 to correct the post-JOI period error (avoiding altogether any POSZ maneuvers). JOI underburns result in more benign PULZ maneuvers, thus the bias in that direction.

OTM- 1 was to be the first maneuver following orbit insertion. As such, it would have to correct for any errors in the Io flyby and the execution of the JOI maneuver. In the presence of many of the fault scenarios and Io approach maneuver decisions, OTM-1 considerations would be paramount. OTM- I was the most difficult maneuver to plan for a number of reasons. Following JOI by only 1.5 days due to solar conjunction constraints, and constrained to be implemented in vector mode within a 17 hour window of opportunity, this would also be the first maneuver implemented following a substantial change in the spacecraft mass properties (i.e. JOI used approximately 55% of the remaining propellant). In addition, there were numerous spacecraft health issues that would have to be addressed in real-time before the OTM could be safely implemented, These included RPM tank overpressure concerns resulting from the largest burn in the mission, excess spacecraft wobble, possible star scanner optics browning due to the high radiation environment (affecting re-establishment of celestial reference following spin down from the JOI maneuver), and any faults that may have occurred during the critical encounter sequence. Two-way Doppler navigation tracking was also necessary to support the design of the OTM. From a non-navigation viewpoint, one-way Doppler is the preferred tracking mode as this telecommunication configuration maximizes telemetry rate and margin. However, reliably stable performance of the onboard oscillator could not be assumed in the high radiation environment close to Jupiter. This stability is critical to make use of one-way Doppler as a navigation data type to reconstruct the Jupiter arrival events. Tracking constraints would delay the start of acquisition of the necessary two-way Doppler until approximately 4 hours after the completion of JOI. Only minimal post-JOI two-way Doppler data was planned for OTM- 1 as the spacecraft telecommunications link would severely degrade if the OTM were to be delayed into the approaching conjunction period, precluding reliable up] ink of the maneuver.

5. IMPLICATIONS OF THE TAPE RECORDER ANOMALY

The Galileo project had, over the previous decade, analyzed and refined a nominal Io approach and orbit insertion *navigation* strategy that was, essentially, discarded in the final days before arrival. In this section the reasons for the change in strategy are discussed and, in a following section, an attempt is made to estimate how the nominal plan might have fared under the actual conditions faced during this phase of the mission.

The navigation strategy on approach to Io was to have corrected three components of miss (B•R, B•T and Time of Closest Approach, see Ref. [8] for coordinate system definition) at each maneuver opportunity in order to conserve propellant, minimize the OTM-1 AV bias and achieve the Io target necessary for science imaging purposes. This did not happen. A single event caused a dramatic change to the navigation strategy for Io approach, JOI and the post-JOI cleanup maneuvers. The Galileo tape recorder exhibited completely unexpected and anomalous behavior in mid-October, 1995, just two months before arrival (see Ref. [1] for a detailed explanation of the anomaly). The unfortunate outcome of this incident was that imaging science and optical navigation imaging (OPNAV) planned for the upcoming Io gravity assist were eliminated. This did, however, allow the navigation strategy to be changed from what had been previously planned.

The change in strategy was made possible for two reasons: First, since there was to be no approach imaging, there was no science requirement to achieve a particular aimpoint. Substantial dispersions from the target could be ignored if the propellant impact could be tolerated. In addition, the Probe-Orbiter relay telecommunications link was robust to significant Io flyby dispersions and was not a limiting factor.

The second reason why the tape recorder anomaly affected the navigation strategy relates to the Phase II flight software. This software (Ref. [10]), which allowed for the return of images at low data rates, was to be uplinked after PJR and relied upon a fully functional tape recorder. Since this was no longer the case, the Phase II software would require significant modifications. Additionally, the observation sequence already planned and designed for a Ganymede l (G l) encounter occurring on July 4, 1996, would have to be completely redesigned to accommodate the anticipated flight software changes. Thus, the original requirement to target to within ±100 km and ±3 minutes of the reference G I aimpoint in order to use the nominal Gl sequence, was no longer justified. Since the sequence had to be redesigned, the project had no concern accepting a variable Gl encounter epoch (the closest approach time could now vary by weeks rather than ±3 minutes as per the nominal plan) which allowed for a much less costly penalty for certain Io flyby and JOI AV errors. This kind of tour redesign option was previously only considered for gross orbit insertion errors.

Figure [3] shows that for JOI overburns or, equivalently, a lower than planned Io flyby altitude, the propellant cost at OTM- 1 could be dramatically reduced by allowing the Ganyrnede 1 (G 1) encounter date to vary by integer Ganymede orbit periods (or equivalently, approximately 1 week increments), and allowing the date of PJR to move over a wider range of dates,

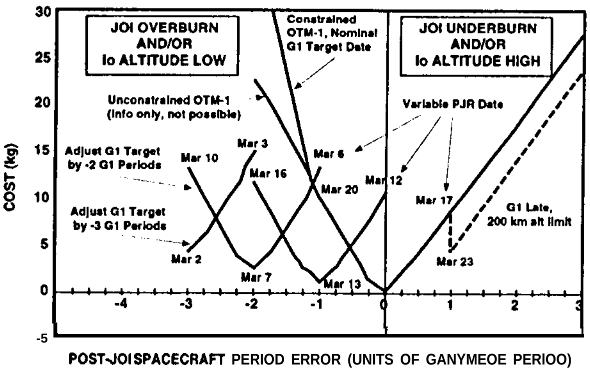

Figure 3. Propellant Cost vs. Post-JOI Period Error

Note that to first order, a post-JOI period error of 1 Ganymede period is equivalent to a 1% JOI execution error or a 100 km Io flyby altitude error. A characteristic of this strategy is that the G2 encounter date did not need to be adjusted for the period errors considered (the time of day changed on the order of a minute), and the remainder of the tour was as planned, A G1 altitude constraint (200 km lower limit) prevented a significant savings from being realized from this strategy for opposite direction Io flyby altitude and JOI execution errors,

6. IO APPROACH AND ORBIT INSERTION RESULTS

TCMS 27 and 28 were cancelled as a direct result of the removal of science aimpoint requirements at Io. The statistically significant component of the error observed at the time of the design of each of those maneuvers happened to be in a benign direction (mostly B*R error), thus there was no propellant cost for canceling the maneuvers. TCM-28A and the JOI tweak were cancelled as a direct result of the G1 targeting strategy discussed above. Table 1 shows that on final approach to Io, OD solutions indicated that the uncorrected trajectory would result in a lower than planned Io flyby altitude. This is precisely where one would bias the trajectory to fully take advantage of this new targeting flexibility at Io and G 1. What would, in the nominal plan, have been a costly error to leave uncorrected (i.e. large cost at OTM-1 to maintain the nominal tour) could be safely ignored by adjusting the G1 encounter date earlier by one Ganymede period and moving the date of PJR earlier by three days. This was the strategy adopted and no trajectory or sequence changes were introduced before JOI. The orbit insertion burn performance was flawless (final reconstruction showed a O. 13% overburn, and less than 1% under performance for the 400N engine), and there were no spacecraft faults during the critical phase. The accurate JOI burn resulted in OTMS 1 and 2 being cancelled, requiring only incremental adjustments to the G 1 target conditions. In addition, the selected post-JOI trajectory design resulted in an additional PJR date adjustment of -1 day, for a total change of -4 days with respect to the nominal date.

The net result was that all of the pre-encounter maneuvers, the JOI tweak, OTM- 1 and OTM-2 were cancelled. All errors were absorbed, essentially, by changing the G 1 closest approach time from July 4, 1996 to June 27, 1996, increasing the G1 altitude by approximately 340 km, changing the latitude of the G 1 flyby by 6°, moving the date of PJR from March 18, 1996 to March 14, 1996, and decreasing the G2 latitude by approximately 5°. A fortunate, yet totally unpredicted and benign navigation scenario resulting from a single anomaly! This benign situation was enabled by anticipating the possible need to redesign the beginning of the tour in case of a gross Io flyby error or orbit insertion anomaly.

7. AN ASSESSMENT OF THE NOMINAL NAVIGATION STRATEGY

A natural question arises from the events described above. How would the nominal strategy have fared had there been no tape recorder anomaly? The following analysis makes use of the actual delivered orbit determination solutions (or trajectory estimates) during this time frame, as well as some engineering judgement, to evaluate the nominal navigation strategy. This strategy had a basic requirement to achieve the Io target and to link with a precise orbital tour for which observation sequences had already been designed. A known shortcoming of this approach is that without the tape recorder anomaly there would have been OPNAVS on Io approach (which may have helped resolve the B*R error on approach). However, the OPNAVS would not have significantly changed the results presented below as the dominant error source detectable by the OPNAVS would have been in the out-of-plane, or B*R, direction. It is likely that only the size of the AV for TCM-28A would have been affected. The B*T error (nearly equivalent to altitude error for this equatorial flyby), which drives the downstream propellant usage, would not have been significantly affected by the OPNAVS. A complete discussion of the orbit determination (OD) strategy and results for the approach phase is discussed in Ref. [11]. Table 1 summarizes the purpose and designation of some of the pertinent OD solutions during this time frame.

Table 1. Orbit Determination Solution Summary for 10 Approach and JOI.

OD Solution	*Purpose of Delivery*	*Altitude (km ± 1 u)*
Target		1000
OD#94	TCM-27 Design	1084 ± 126
OD#95	TCM-28 Design	1080 ± 145
OD#96	TCM-28A Design	937 ± 36
OD#97P1	JOI Tweak Status	900 ± 28
OD#97P2	JOI Tweak Design	888 ± 27
OIM100	Post 10 Solution	892 ± 2
OD#101	OTM-1 Design	JOI = +0. 1%

At the time of OD#94 and the design of TCM-27, the miss from the target was estimated to be 118 km in B•R (σ = 120 km), 78 km in B•T (σ = 131 km) and -5 seconds in the time of closest approach (TCA, σ = 10.5 seconds). The error was large and statistically significant (greater than 1 σ), important to remove for the science observation sequence, and would likely have been corrected at this time (for a AV of approximately 0.2 m/see). For this study, TCM-27 is implemented.

At the time of OD#95 and the design of TCM-28, the trajectory estimate (which in this scenario includes a nominal TCM-27) shows that the miss from the target would have been approximately 21 km in B•R (σ = 102 km), 6 km in B•T (σ = 150 km) and 0.6 seconds in TCA (σ = 12 seconds). The difference between the predicted Io flyby conditions and the target would have been small compared to the OD uncertainties. It also shows that if TCM-27 had not been implemented, TCM-28 would have been implemented as the OD solutions are consistent and it would have made no sense to wait until TCM-28A to make the correction. (The OPNAVS would have reduced the B*R uncertainty and made either of these TCM corrections more accurate.)

At the time of OD#96 and the design of TCM-28A, the trajectory estimate (which again includes a nominal TCM-27) shows that the miss from the target would have been approximately 215 km in B•R (σ = 70 km), -172 km in B•T (σ = 34 km) and 14.3 seconds in TCA (σ = 2.1 seconds). It is safe to say that TCM-28A would have been implemented with this kind of error in the Io bplane (a very large altitude error). For this study, a TCM-28A AV of approximately 1.0 m/sec would have been required to adjust the trajectory to achieve the desired Io target.

OD#97P2 is the OD solution that most closely approximates the trajectory estimate that would have been supplied for the JOI Tweak design. Propagating 0D#97P2 with a TCM-27 and a TCM-28A results in a miss at Io of approximately -28 km in B•R (σ = 71 km), -45 km in B*T (σ = 23 km) and 3.6 seconds in TCA (σ = 0.8 seconds). With this information, a JOI tweak would have been statistically significant. Not implementing a JOI Tweak in this example would have resulted in a predicted bias of 8 m/see at OTM-1 (purely LAT maneuver) or 15 m/see if one were to wait until OTM-2 to make the same correction. Uplinking a change to the thoroughly tested critical sequence during such an intense period of time for the flight team and the spacecraft (possibly adding an incremental risk to the acquisition of the probe data and orbit insertion), would have been balanced against the relatively small predicted propellant savings of 4 kg for uplinking a tweak.

The observed performance at JOI (approximately +.1 % at the time of OTM-1 design) and the best estimate of the Io flyby at that time (OD#1 00) is used to determine the AV that might have been necessary at OTM- I to navigate the tour as originally designed, for each of the JOI tweak scenarios (again including TCM-27 and TCM-28A). Under these assumptions, OTM- 1 would have required less than 1 m/see if JOI had been tweaked (PJR moving to 19-MAR- 1996 in this scenario) or approximately 11 m/see LAT if JOI had not been tweaked. If a fault were to occur, preventing the implementation of OTM- 1, the AV required at OTM-2 would have been approximately 27 m/see (the net cost to the mission would have been approximately 10 m/see as the PJR AV to achieve the desired G 1 target decreased in this particular scenario).

This academic exercise does show that the navigation strategy would have performed as expected and that the spacecraft could have satisfied the Io science objectives, while maintaining the nominal G1 encounter date and the designed G I and G2 encounter sequences.

8. ORBITAL TOUR

The prime mission consists of ten targeted encounters accomplished in eleven orbits about Jupiter. Figure 4 illustrates the tour trajectory, the design and characteristics of which design are discussed in Ref. [12].

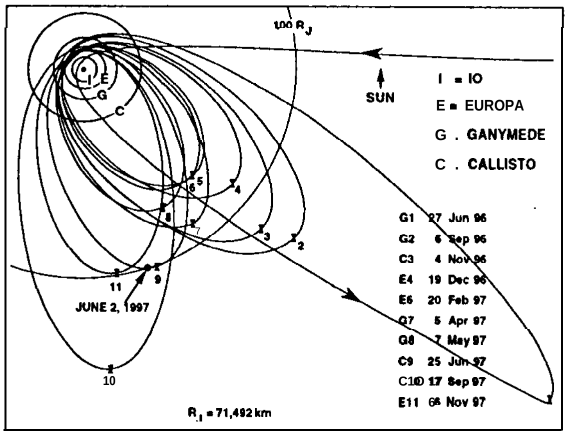

Figure 4. Orbital Tour Trajectory

During each orbit there are, typically, three orbit trim maneuvers, or OTMS, planned. A summary of approach and orbital tour maneuver location information is given in Table 2. The first two orbits about Jupiter, leading up to encounters with G 1 and G2, have an additional maneuver on approach to the encounters. These additional maneuvers protected the mission from catastrophic propellant cost scenarios resulting from the loss of a single OTM opportunity (e.g. a ground or spacecraft fault precluding the implementation of a necessary pre-encounter maneuver).

Table 2. Comparison of Predicted AV with Implemented ΔV for 10 Approach and the Orbital Tour (to date)

Maneuve Number	*Event Description*	*Event Time (UTC-SCET)*	*Flyby Altituc (km)*	*Days wrt Next Encounter*	*Predicte Mean (m/s)*	*Predicte ΔV(90) (m/s)*	*Actual ΔV (m/s)*	*N σ wrt Mean*
	Probe Release	13-Jul-1995 05:30:00		-147.51				
TCM-25A	00N Calibratic	24-Jul-1995 070000		-136.45			*0.42*	
TCM-25	ODM	27-Ju1-199507:OO:OC		-133.45	62.2	*62.2*	*61.85*	
TCM-26	Io -100 days	29-Aug-1995 01:00:20		-100.70	0.3	0.7	*0.98*	2.9
TCM-27	Io -20 days	17-Nov-1995 19:30:00		-19.93	1.2	2.5	cancelled	-1.3
TCM-28	Io -10 days	27-Nov-1995 19:30:00		-9.93	0.3	0.5	cancelled	-2.0
TCM-28A	10-5 days	02-Dec-1995 23:30:00		-4.76	0.4	0.7	cancel led	-1.9
	Europa	07-Dec-1995 130852	32994	-0.19				
	10	07-Dec-1995 17:45:58	897	-202.53				
	upiter Periaps:	07-Dec-1995 21:53:44	21457!	-201.36				
	Probe Entry	07-Dec-1995 22:04:44	450	-202.35				
TCM-29	JOI	08-Dec-1995 00:27:26		-202.25	643.8	650.6	644.40	0.1
OTM-1	JOI + 1.5 days	09-Dec-199513:05:OQ		-200.73	3.0	8.1	cancelled	-0,8
OTM-2	JOI + 26 days	02-Jan-1996 19:25:00		-176.46	0.0	0.0	cancel led	-0.3
OTM-3	PJR	14-Mar-1996 19:15:00		-104.47	375.8	376.9	377.91	2.7
OTM-4	'JR + 50.0 Day	03-May-1996 17:45:20		-54.53	1.4	1.6	1.28	-1.2
OTM-5	G1 -14.6 Days	12-Jun-1996 14:55:20		-14.65	0.3	0.5	0.52	2.2
OTM-6	G1 -2.5 Days	24-Jun-19961850:2C		-2.49	0.7	1.2	0.48	-0.7
	Ganymede 1	27-Jun-1996 06:29:07	835	-71,52				
0TM-7A	G1+3.1 Days	30-Jun-199608:09:2C		-68.45	7.3	16.0	0.58	-1.1
OTM-7B	G1+6.1 Days	03-Jul-1996 09:00:00		-65.42			ontingenc	
OTM-8	G1 + Apo	05-Aug-1996 08:24:20		-32.44	4.6	5.0	4 . 6 6	0.1
OTM-9	G2 -10.0 Days	27-Aug-1996 18:10:20		-10.03	0.2	0.4	0.08	-1.2
OTM-10	G2 -2.0 Days	04-Sep-199619:14:OC		-1.99	0.3	0.5	cancel led	-1.5
	Ganymede 2	06-Sep-1996 18:59:34	261	-58.77				
OTM-11	G2+3.1 Days	09-Sep-1996 21:50:20		-55.66	2.9	5.8	4.35	0.9
OTM-12	G2 + Apo	08-Ott-1996 14:54:20		-26.94	0.5	1.0	0.59	0.2
OTM-13	C3 -3.0 Days	01-Nov-1996 14:10:00		-2.98	0.4	0.6	cancel led	-2.0
	Callisto 3	04-Nov-1996 13:34:28	1136	-44.72				
	Europa 3A	06-Nov-1996 18:49:55	34824	-42.50				
OTM-14	C3 + 5.7 Days	1O-NOV-1996 07:24:18		-38.98	3.8	7.0	2.33	-0.6
OTM-15	C3 + Apo	26-Nov-1996 11:54:20		-22.79	1.3	2.8	0.24	-1.0
OTM-16	E4 -3.2 Days	16-Dec-1996 02:54:20		-3.17	0.6	1.2.	0.11	-1.2
	Europa 4	19-Dec-1996 06:52:57	692	-31.76				
OTM-17	E4 + 4.2 Days	23-Dec-1996 11:50:18		-27.56	"2.0	4.1	1.97	0.0
OTM-18	E4 + Apo	04-Jan-1997 14:30:00		-15.45	1.3	2.6	cancel led	-1.4
	Europa 5A	20-Jan-1997 01:12:02	26668	-31.66				
OTM-19	Orbit 5 Apo	06-Feb-1997 13:00:00		-14.17	1.7	3.0	0.84	-0.8
0TM-20	E6 -2.0 Days	18-Feb-19971735:OC		-1.98	0.4	0.7	cancelled	-2.0
	Europa 6	20-Feb-1997 170311	586	-43.59				
OTM-21	E6 + 3.6 Days	24-Feb-1997 06:52:00		-40.01	3,1	6.9	0.91	-0.8
OTM-22	E6 + Apo	14-Mar-1997 01:15:00		-22.25	15.6	17.1	16.00	0.3
OTM-23	G7 -4.1 Days	01-Apr-1997 05:00:00		-4.09	1.5	2.7	1.05	-0.5
	Europa 7A	04-Apr-1997 05:58:48	23487	-1.05				
	Ganymede 7	05-Apr-1997 07:09:58	3102	-32.37				
OTM-24	G7 + 3.0 Days	08-Am-1997 08:20:00		-29.32	1.5	3.1	0.58	-0.7
OTM-25	G7 + APO	21-Apr-1997 12:40:00		-16.14	0.1	0.2	0.14	0.4

An additional maneuver opportunity was planned on the outbound leg after G-l **(OTM-7B)** "to protect against a contingency scenario where the Phase 11 flight software, and in particular the new onboard OPNAV algorithm, failed to perform as expected (either because of a fault or a development delay). Needless to say, none of this came to be and the flight software was a tremendous engineering success. The only spacecraft fault which threatened the implementation of an OTM occurred on August 24, 1996 when the spacecraft entered **safing** just three **days** before **OTM-9** was to execute. Recall that this maneuver was added to protect against such an event occurring near the next maneuver, **OTM-** 10! The spacecraft recovery by the flight team was outstanding. **OTM-9** was executed on time, just three days after the event, using just one string of what is typically a dual-string (redundant) onboard computer process. This capability had been tested as a contingency for just this scenario.

A useful metric for measuring the success of the OTM planning process is through a comparison of predictions to the actual AV implemented in the mission. This comparison is provided in Table 2 and shows that the statistical AV corrections to maintain the desired orbital tour trajectory have been minimal and will allow for sufficient propellant margin at the end of the primary mission to complete the objectives of an extended mission.

A quick glance down the final column of Table 2 shows that the majority of the planned maneuvers have been less than the predicted mean. This is due, primarily, to the better than predicted orbit determination accuracy thus far in the mission. The radiometric and OPNAV navigation data types have allowed for the orbit determination accuracy and analysis to be superb. The OD process has improved the Galilean satellites ephemeris accuracy sufficiently such that there is no future necessity for the OPNAV data type to navigate the remainder of the prime mission or even the extended mission. Also, since PJR, four OTMS have been cancelled. When science data quality is unaffected, and propellant costs are minimal, then the conservative and prudent strategy has been to avoid any incremental risk to the spacecraft and encounter science data that may be associated with the design and uplink of a propulsive maneuver (i.e. minimize flight team and spacecraft activities).

9. FUTURE EVENTS

As we near the end of the prime mission, planning is proceeding for a two year extended mission, referred to as the Galileo Europa Mission, or GEM. Following the formal end of prime mission operations on December 7, 1997, there will be an attempt to sustain operations through an additional fourteen encounters (8 with Europa, 4 with Callisto and 2 with Io) of the Galilean satellites, ending with return visits to Io in October and November of 1999. Survival and health of the spacecraft hardware, following repeated plunges through the near-Jupiter radiation environment, will likely be the determining factor for completion of the GEM. Propellant usage to date, and propellant predictions through the end of the GEM indicate that sufficient margin is available to navigate the two year mission (>95% likelihood of an Io 25 flyby).

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11. REFERENCES

[1] W. J. O'Neil, N. E. Ausman Jr., J. A. Gleason. M. R. Landano, J. C. Marr, R. T. Mitchell, R. J. Reichert, M. A. Smith, "Project Galileo At Jupiter", Paper IA F-96 -Q.2.01, presented at the 47th Congress of the International Astronautical Federation, Beijing, China, 7-11 October 1996.

[2] Science Magazine, "Galileo Orbiter", American Association for the Advancement of Science, Vol. 274, No. 5286, 18 October 1996 (pp. 377- 403).

[3] C. T. Russell, cd., "The Galileo Mission", Space Science Reviews, Vol. 60, Nos. 1-4, May 1992 (pp. t - 616).

[4] Science Magazine, "Galileo probe", American Association for the Advancement of Science, Vol. 272, No. 5263, 10 May 1996 (pp. 837- 860).

[5] L. A. D Amario, et. al., "Navigation Strategy for the Galileo Jupiter Encounter and Orbital Tour", AAS Paper 95-381, presented at the AAS/AIAA Astrodynamics Specialist Conference, Halifax, Nova Scotia, Canada, 14-17 August 1995.

[6] W. J. O'Neil, N. E. Ausman Jr., M. R. Landano, M. A. Smith, "Galileo On Jupiter Approach", Paper IAF-95-Q.5.06, presented at the 46th Congress of the International Astronautical Federation, Oslo. Norway, 2-6 October 1995.

[7] L. A, D'Amario, "Navigation of tbe Galileo Spacecraft", Proceedings of The Three Galileos Conference, Padova, Italy, January 1997 (in preparation).

[8] C. L. Potts, M. G. Wilson, "Maneuver Design for the Galileo VEEGA Trajectory", AAS Paper 93-S66, presented at the AAS/AIAA Astrodynamics Specialist Conference. Victoria, B.C., Canada, 16-19 August 1993.

[9] Barber, T. J., Krug, F. A., Renner, K. P., "Final Galileo Propulsion System In-Flight Characterization", AIAA Paper 97-2946, to be presented at the AIAA/ASME/SAE/ASEE 33rd Joint Propulsion Conference and Exhibit, Seattle, WA, 6-9 July 1997.

10] W. J. O'Neil, N. E. Ausman Jr., T. V. Johnson, M. R. Landano, and J. C. Marr, "Performing the Galileo Jupiter Mission with the Low-Gain Antenna (LGA) and Enroute Progress Report", Paper IAF-93-Q.5.4 11, presented at tbe 44th Congress of the International Astronautical Federation, Graz, Austria, 16-22 October 1993.

11] R. J. Haw, et. al., "Galileo at Jupiter: Delivery Accuracy", AIAA Paper 96-3613, presented at the AIAA/AAS Astrodynamics Specialist Conference, San Diego, California, 29-31 July 1996.

[12] A. A. Wolf, D. V. Byrnes, "Design of the Galileo Satellite Tour", AAS Paper 93-567, presented at the AAS/AIAA Astrodynamics Specialist Conference, Victoria, B. C., Canada, 16-19 August 1993.